

Identification of Intra-Bunch Transverse Dynamics for Model-Based Wideband Feedback Control at CERN Super Proton Synchrotron¹

O. Turgut^{1,6}

J. Dusatko¹, J. D. Fox¹, C. Rivetta¹, W. Hofle², U. Wehrle², K. Li²
S.M. Rock⁶ and other LARP Ecloud Contributors^{1 2 3 4 5}

¹ARD, SLAC, ²BE-ABP-ICE Groups, CERN, ³Lawrence Berkeley Laboratory
⁴LNF-INFN, ⁵KEK, ⁶Stanford University

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Outline

- Introduction and Problem Definition
- Existing Intra-Bunch Feedback Approach
- Intra-Bunch Dynamics Identification
 - Nonlinear Macro Particle Simulation Data
- Model-Based Controller Efforts
 - Reduced Order Model Closed Loop Simulations
- Conclusions and Future Work

Intra-Bunch Dynamics Control

- HiLumi - LHC intensities - potential Electron Cloud and Transverse Mode Coupling instabilities in SPS.
- Control intra-bunch dynamics in SPS and LHC with wideband feedback system - 1 Ghz bandwidth - 1.7 ns proton bunch.
- Alternative methods exist, the wideband feedback system is a flexible complimentary solution.
- Intra-bunch feedback in JPARC, but for longer bunches. This is an effort for higher bandwidth.

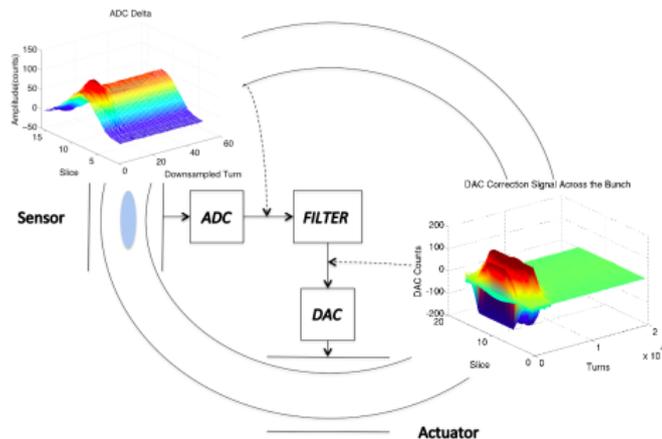
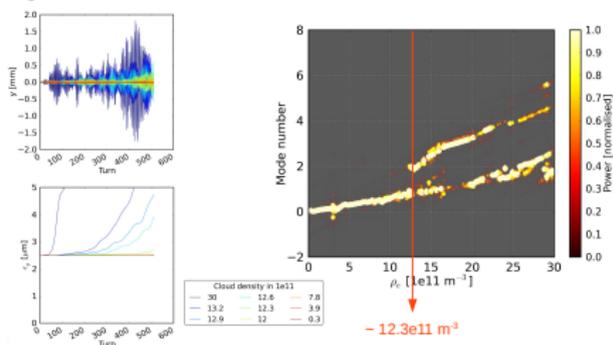


Figure: Multiple samples across the bunch are used to sense and interact with the bunch.

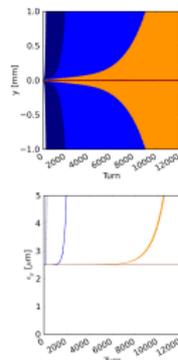
Nonlinear Effects / Instability Thresholds for High Intensity

- Q20 Optics, $f_\beta = 0.185$, $f_s = 0.017$.
- HeadTail simulation studies.
- Anticipating unstable frequencies up to a GHz and many modes to be unstable.

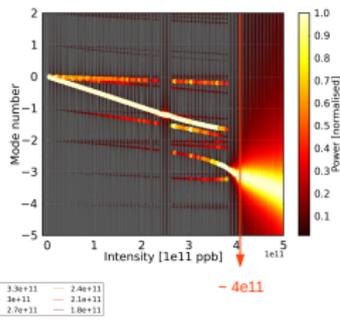
$$\rho_e = [1 - 30] \times 1e11 \text{ m}^{-3} \text{ (from red over green to blue)}$$



: Electron cloud instability.

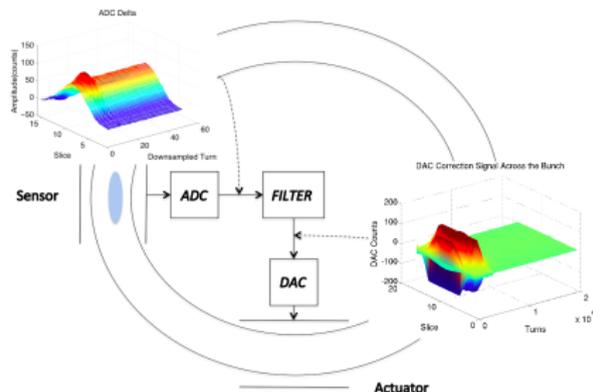


: Transverse mode coupling instability.

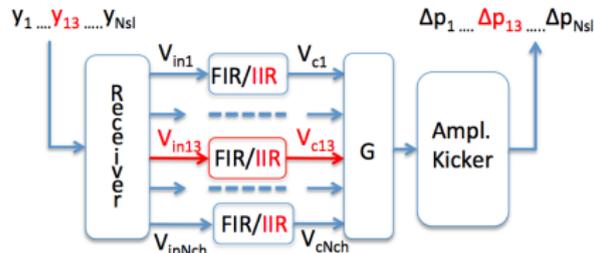


Wideband Feedback Control with Diagonal Architecture

- One approach is a **parallel processing diagonal control filter architecture**.
- N parallel independent filters.
- Vertical position (dipole) measurements are sampled across the bunch, the feedback correction signal for slice i is only computed based on measurements of slice i over the last n turns.



: Multiple samples across the bunch are used to sense and interact with the bunch.



: Diagonal Architecture in Wideband Feedback Demonstration System at CERN.

FIR Filter - Design and Limits

- Diagonal FIR filters : computationally efficient.
- Control filters remove orbit offsets, reduce noise, apply frequency selective phase shifts.
- Diagonal filters can limit the maximum damping and stability of multiple modes with large tune shifts.
- Small separation of betatron and synchrotron tunes, difficult to stabilize motion with FIR filters.

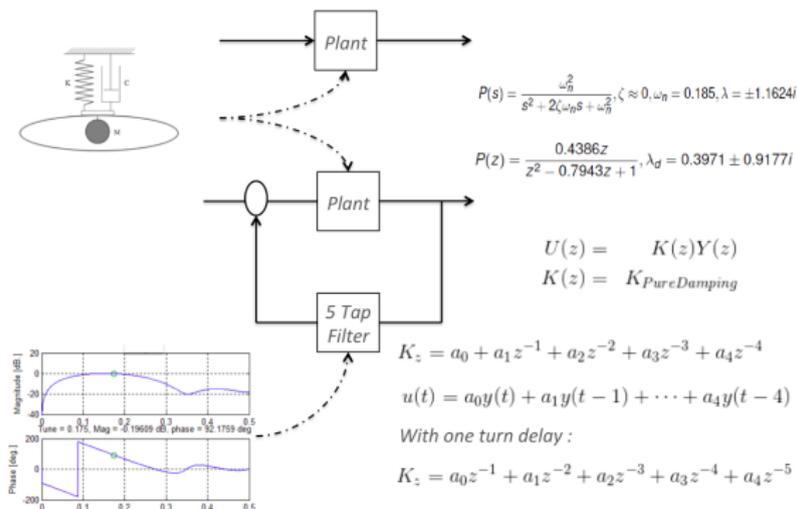


Figure: Illustrative N tap FIR filter is designed and tuned for specific frequency.

Model-Based Controller Design Approach

- Model-based multi-input multi-output (MIMO) controller do not have those limitations, at the expense of a more complexity $\mathcal{O}(n^2)$.
- Modeling and identification of the intra-bunch dynamics are needed.
- We present linear reduced order MIMO models and use them to **design model-based MIMO feedback controllers**.

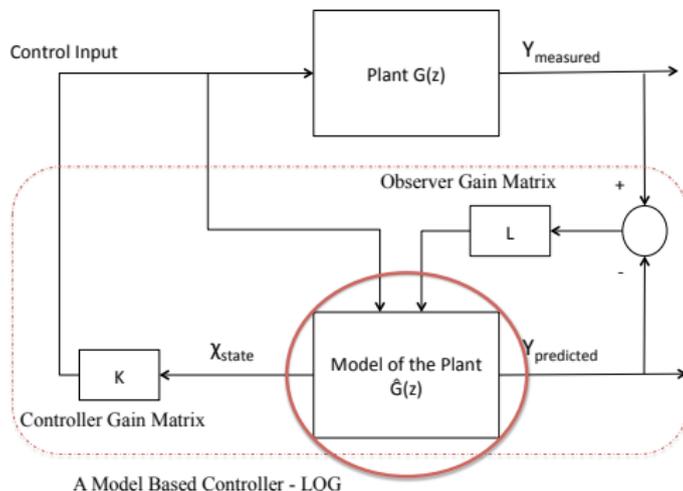
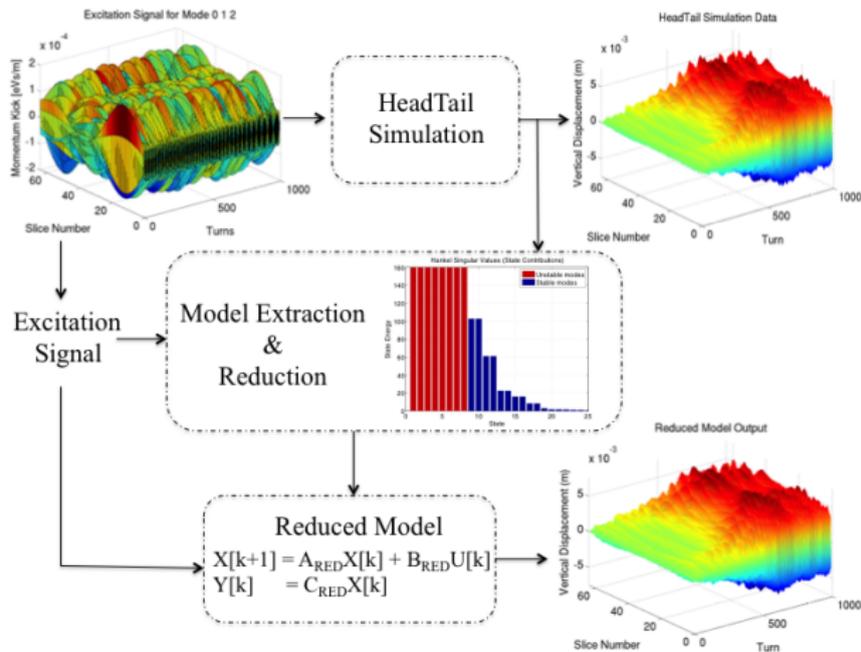


Figure: A model-based controller design closed loop block diagram.

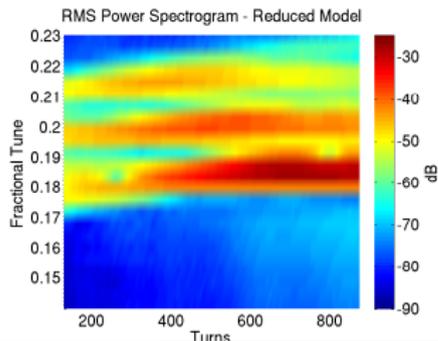
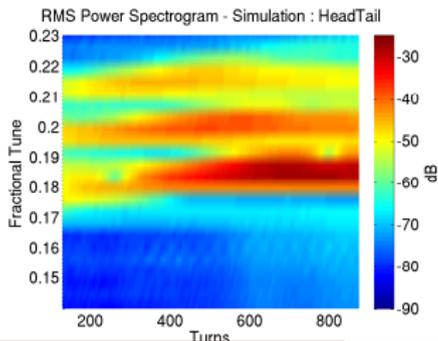
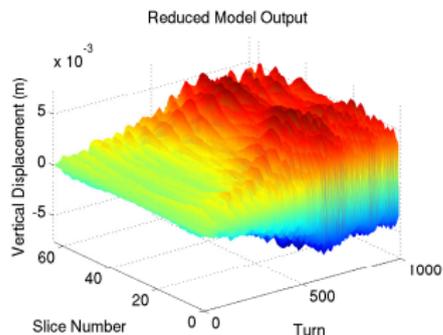
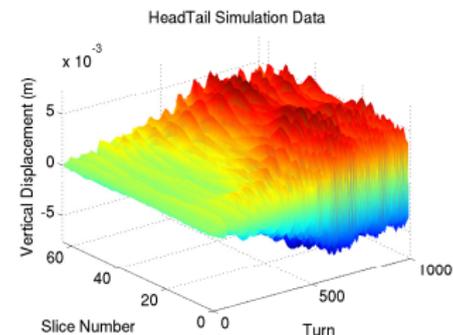
Reduced Model from Open Loop Simulations



- Parameters of the model for modes 0, 1 and 2 dynamics are identified using open loop simulation data.
- We use the same excitation signal to drive the reduced order model and compare the time domain result with HeadTail simulation result for model verification.
- This model is used to design a model-based controller (Discrete-time linear quadratic optimal controller).

Comparison of HEADTAIL with Reduced Model

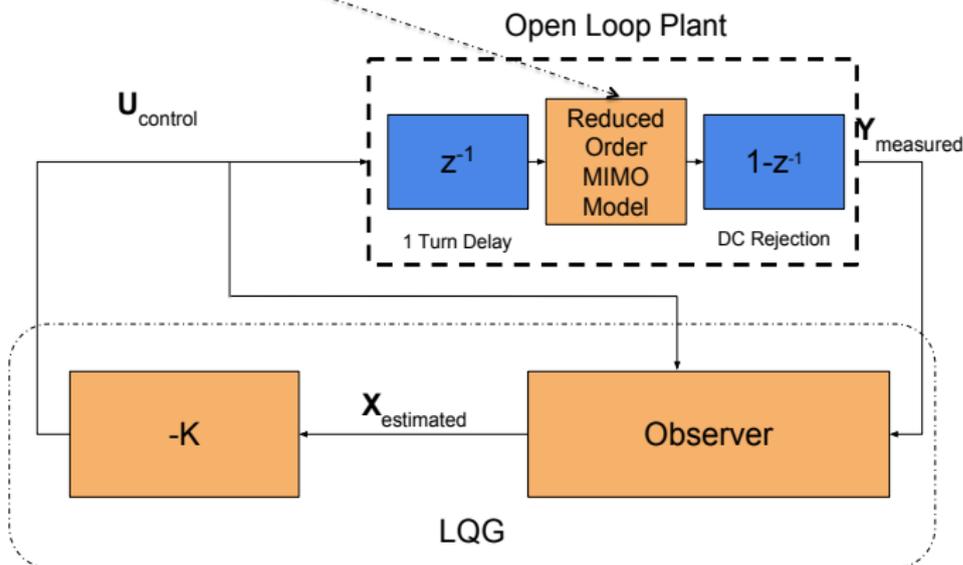
- Response of intra-bunch dynamics for a 0.175 - 0.22 frequency sweep excitation over 1000 Turns.
- The vertical displacement and corresponding spectrograms of the HeadTail simulation and the reduced order MIMO model are shown. The simulation data and the reduced order model response show good agreement in time and frequency domain.



Model-Based Controller - Closed Loop Design

Reduce Model

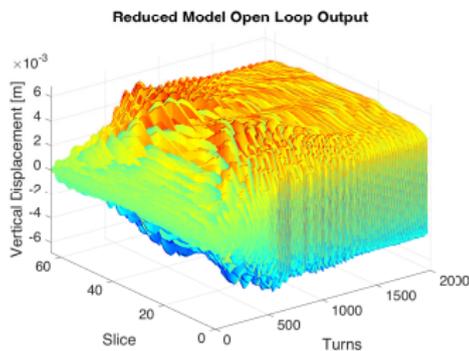
$$\begin{aligned} X[k+1] &= A_{\text{RED}}X[k] + B_{\text{RED}}U[k] \\ Y[k] &= C_{\text{RED}}X[k] \end{aligned}$$



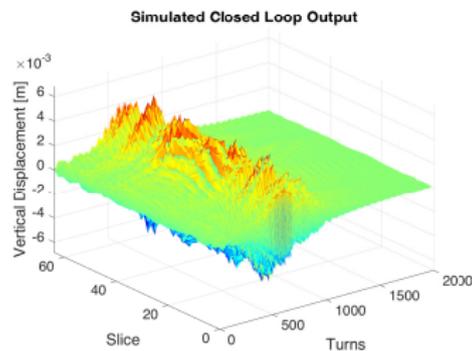
- Open loop dynamics must be augmented to include intrinsic 1 turn delay and orbital offset rejection in the controller design.

Closed Loop Dynamics - Simulated at MATLAB

- Controller based on open loop reduced order MIMO model.
- Excitation lasts for 1000 turns and the rest is free response.
- Open loop damping : 909 and 625 turns \rightarrow Closed loop damping : 169 and 126 turns, respectively.



: Open loop driven response time domain trajectory.



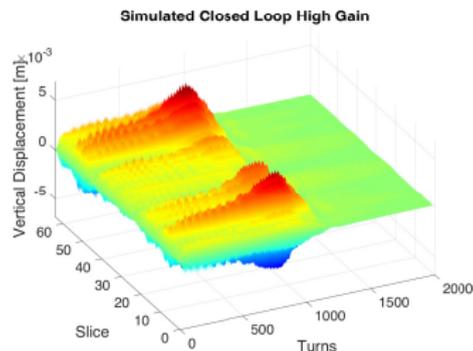
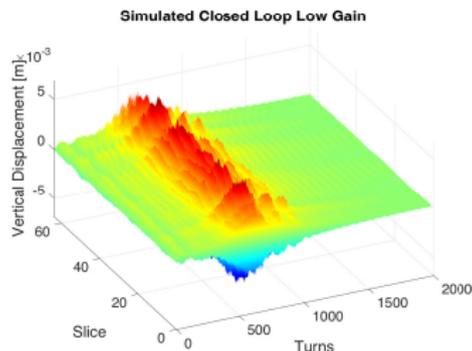
: MATLAB simulated closed loop driven response time domain trajectory.

Intra-Bunch Dynamics

MODE	OL (Turns)	CL (Turns)
0	$-0.000 \pm 0.1850i$ (∞)	$-0.0048 \pm 0.1850i$ (208)
1	$-0.0011 \pm 0.2015i$ (909)	$-0.0058 \pm 0.2012i$ (169)
2	$-0.0016 \pm 0.2181i$ (625)	$-0.0079 \pm 0.2181i$ (126)

Closed Loop Dynamics - Simulated at MATLAB

- Easy to modify the controller to increase the damping on individual modes.
- No shift in tune - resistive control !
- Further damping : 169 and 126 turns \rightarrow 12.5 and 14.1 turns, respectively.



: Closed Loop with Low Feedback Gain

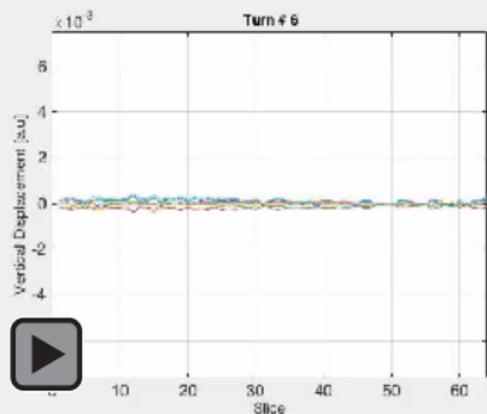
: Closed Loop with High Feedback Gain

Intra-Bunch Dynamics (Damping time constant)

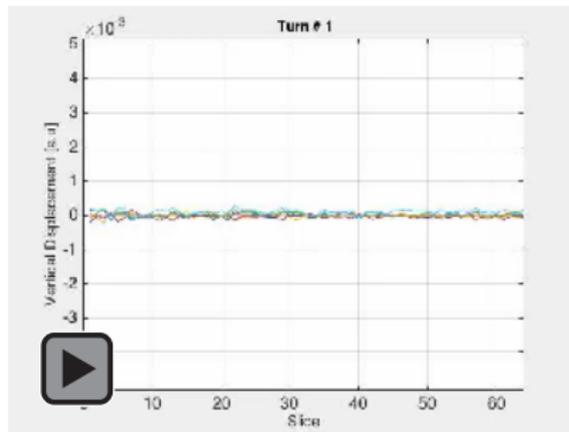
MODE	OL	CL Low Gain	CL High Gain
0	no damping	208	40.8
1	909	169	12.5
2	625	126	14.1

Model-Based MIMO Feedback

- Excitation signal tailored to excite modes 0, 1, and 2 (betatron oscillations, 1st and 2nd upper sidebands).
- The reduced order model-based MIMO controller significantly increases the **damping on each mode**. The **vertical motion is well controlled and decays to noise floor after excitation stops**.



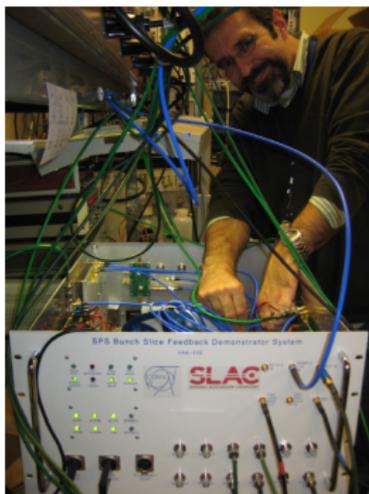
(a) Open Loop Response of Reduced Order Model - Mode 0, 1, 2 Driven



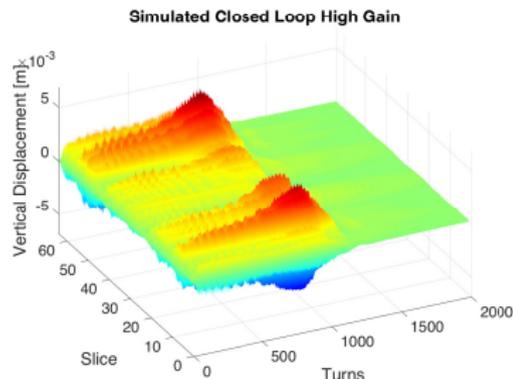
(b) Closed Loop Response of Reduced Order Model - Mode 0, 1, 2 Driven

Conclusion and Future Work

- Model-based MIMO control : Results are very promising.
- This kind of damper might have better performance compared diagonal FIR filters.
- Approach is easily applicable to other machines, other control tasks at accelerators.
- This design method works with data from physical measurements as well as from simulations.
- Reprogrammable logic change is enough - looking forward to implementing in SPS within existing wideband feedback demonstration system.



: Wideband Feedback in the SPS.



: Closed Loop Damping Intra-Bunch Modes

Thank You for Your Attention

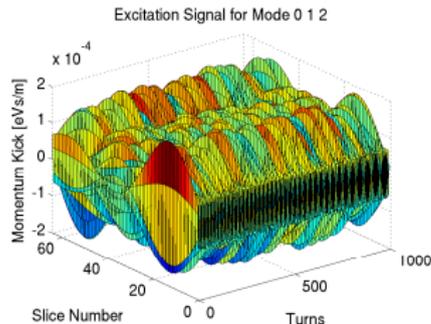
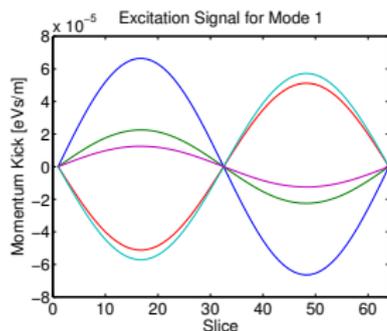
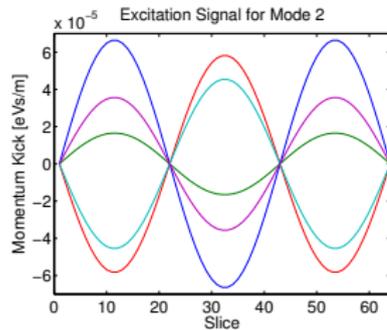
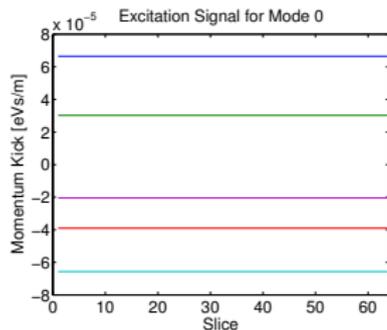
- Any Questions ?
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- Thanks to NSF for travel support to IPAC'16.



Extra Material

Persistent Input - Excitation Signals

- Amplitude distribution of the excitation across the bunch and the modulation of the amplitude shown for first 5 turns. Amplitude modulation of each excitation is done by a frequency sweep. Sweep for \vec{U}_{mode0} covers 0.175-0.195, \vec{U}_{mode1} covers 0.195-0.21 and \vec{U}_{mode2} covers 0.21-0.23 fractional tunes covering an overall band of betatron tune to 2nd upper sideband.



FIR vs Model Based - Initial Results

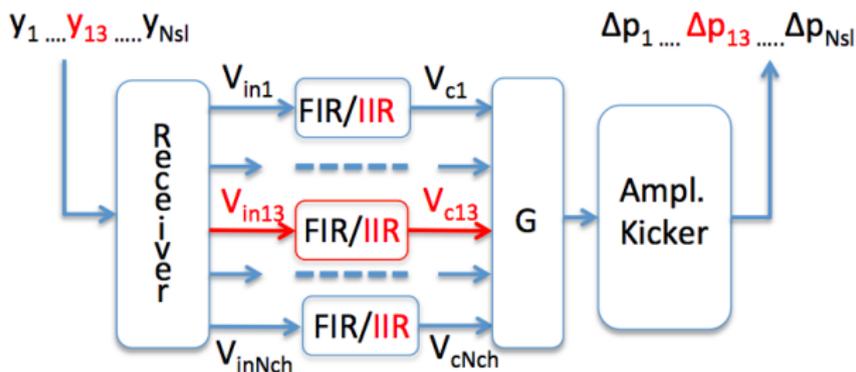


Figure: Diagonal Controller Architecture in HeadTail - FIR vs IIR, Courtesy: Claudio Rivetta

		<i>Model Based IIR</i>	<i>5 Tap FIR</i>
<i>Open Loop Dynamics</i>	Mode 0	$-0.000 \pm 0.185i$	
<i>Closed Loop Dynamics</i>	Mode 0	$-0.0074 \pm 0.183i$	$-0.0074 \pm 0.185i$
	Mode 1	$-0.0037 \pm 0.199i$	$-0.0026 \pm 0.2i$